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ELECTRICAL CONTACT MATERIALS FOR SPACE VEHICLE SYSTEMS

Phase I Report - ARF Project E171

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ABSTRACT

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A literature survey on electrical contact materials was performed to determine present practices in the specification of materials for low-level electrical contacts. Special emphasis was placed on material properties, and methods for evaluation of low-level contacts. The literature review comprises Phase I of a study and experimental investigation to determine the most suitable contact materials for use in connectors and contacts for space vehicle systems, as well as ground support equipment. A brief analysis of the weather parameters in the Cape Canaveral region was also carried out during this phase.

The literature review indicated that the ideal material for low-level contacts must be tarnish and corrosion free and have high conductivity. In addition, it must have a low coefficient of friction to minimize insertion and withdrawal forces. Gold approaches these requirements very closely, and has found wide application, particularly as a plating material. Hard gold alloys are often used to obtain satisfactory wear properties at a lower cost. Even with gold plated contacts, corrosion failures can occur because of the porosity of most commercial plates, and the possible diffusion of base metal to the surface.

Author

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ELECTRICAL CONTACT MATERIALS FOR SPACE VEHICLE SYSTEMS

I. INTRODUCTION

This report summarizes the results of the literature survey (Phase I) on electrical contact materials for Project No. E171, "Electrical Contact Materials for Space Vehicle Systems." This work is sponsored by the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, and has as its object the determination of optimum materials and processes for obtaining reliable electrical connections in space vehicle systems.

The area of interest to NASA in this study involves any contacts or connectors in low power signal and control circuits. The signal or electrical levels specified for study were as follows:

a. Current ranges between 1 microampere and 5 amperes, AC and DC

b. High impedance circuits with source voltages between 200 millivolts and 500 volts, AC and DC.

Contact operation under two environments was specified; air conditioned blockhouse and exposure to atmospheric elements at Cape Canaveral, Florida.

Electric contacts in space vehicle systems are generally subjected to severe environmental stresses, and the selection of suitable materials requires careful consideration of many interrelated factors in order to achieve the necessary reliability levels. The nature of the equipments and circuits is such that a majority of the contact pairs are operated in the low-level area, an area in which corrosion phenomena exerts a strong influence on the behavior of the contact interfaces. The low-level area is loosely defined as that area of contact operation in which

only mechanical forces can alter the condition of contact interfaces. In this area, the current and voltage magnitudes are such that thermal and voltage breakdown effects do not significantly influence the condition of the contact surfaces. Such magnitudes are generally in the low microampere and millivolt ranges. To obtain high performance, reliable low-level contacts, materials must be selected that have unusually high resistance to corrosion and contamination.

The electrical contact between two metallic surfaces occurs at a relatively few metallic spots or projections that are in physical contact when the surfaces are mated. The current density is high at the points of contact because the total current flow is concentrated in a small percentage of the contact surface, and as a result, the effective resistance is substantially higher than that determined by the bulk resistance of the contact material. Because of this effect, the contact material must have good conductivity to minimize the voltage drop across the contact pair.

The presence of an insulating film on the contact surfaces prevents metal to metal contact, and conduction occurs only when the film is ruptured by mechanical, electrical or thermal action. In the low-level area, film disruption generally results only from mechanical effects such as abrasion, wipe, impact and deformation because electrical and thermal effects are usually negligible. In cases where the film is of monomolecular thickness, conduction can occur by the tunneling effect.

Much of the recent literature on the subject of low-level, low-power contacts has been reviewed to determine the present state of the art and also to determine areas that require additional research and development in order to facilitate higher levels of performance and reliability.

Special emphasis was placed on material properties and characteristics and also methods for evaluation of low-level contacts. It should be noted that a vast amount of reference material is available on the general subject of contacts, and although this material provides background and general insight, the results are not generally applicable to the particular problem of low-level contacts. Only in recent years has there been concerted research activity in dry circuit contacts, with a large portion being carried out in foreign countries.

The report summarizes the results of the literature review and presents some general conclusions regarding materials for low-level contacts. It should be pointed out that, besides the actual contacting mechanism, many other factors influence the over-all usefulness and reliability of an electrical connector. These factors include termination characteristics (soldering, crimping, welding), seal adequacy, durability, and maintainability.

Also included as a part of this report is a tabulation and summary of weather parameters for the Cape Canaveral region. This material is presented as Appendix A of this report. A discussion of salt-spray conditions and their influence on corrosion has been included.

II. PHYSICAL PROPERTIES REQUIRED IN ELECTRICAL CONTACT MATERIALS

A. Electrical Conductivity

Electrical contacts should possess good electrical conductivity in order to minimize resistance heating due to the passage of current. Even in low-current circuits, the conductivity must be high to minimize constriction resistance and the associated voltage drop across the contact pair.

B. Thermal Conductivity

The factor of good thermal conductivity in electrical contacts is most important in high current applications and in circuits where heating due to arcing occurs. Good thermal conductivity in the contact material will assist in keeping the local temperatures low thus helping to prevent oxidation.

C. Resistance to Oxidation and Tarnishing

A prime requisite of electrical contact materials is that they make intimate, metallic contact with each other. This condition is difficult to realize if any type of surface films due to oxidation or tarnish develop on the mating areas. It is thus apparent that a material selected for electrical contacts must be reasonably free of oxidation or filming tendencies under the imposed service conditions. There are accessory considerations in regard to this requirement involving the degree of wipe, contact forces and open circuit voltages that would have a bearing on the thickness of insulative films that could be tolerated in any given case. High contact forces coupled with an appreciable wiping action would mechanically rupture some films and restore the contact. In cases where the open circuit voltages are high enough to produce "fritting," the film is broken down by an electric discharge mechanism and contact is restored. In low-level, low force contacts, however, these conditions do not apply and it is necessary to rely on the inherent stability of the contact surfaces for satisfactory contact.

Another type of filming phenomenon is sometimes observed in dry circuit contacts. A brownish powdery material appears on the contacts and is converted to a polymer-like material as the contacts are made and broken. The brownish deposit is attributed to the presence of organic

vapors in the vicinity of the contacts. The polymer-forming tendency varies for various metals being greatest for the members of the platinum family. One method for eliminating this type of filming would be to prevent the presence of organic vapors in the contact region, but in practice this is difficult. Most contacts are carried in or associated with insulators derived from organic based materials.

D. Contact Resistance

Contact resistance has an important bearing on the life and reliability of electric contacts. Buildup of resistance during operation may cause an increase in temperature, which in turn may accelerate oxidation or film formation and lead to an eventual open circuit condition. The overall contact resistance of a pair of contacts is determined by three factors:

Bulk Resistance

This is the volume resistance of the body of the contact material and depends upon the specific electrical conductivity of the material and the dimensions of the contact.

Constriction Resistance

When two metal surfaces are mated, the area of actual contact (on a micro-scale) is considerably different from the apparent mated area based on the dimensions of the pieces. Only the high points of the two surfaces actually contact each other, and the real area of contact - as far as current carrying considerations are concerned - is only a fraction of the apparent contacting area. This phenomenon causes the current to be concentrated in a number of small diameter parallel paths at the interface between the two contacts. The resistance of these paths is considerably higher than would be obtained if perfect mechanical mating of the surfaces could be achieved, and is known as the constriction resistance. Constriction

resistance is a function of the deformability (hardness, ductility and strength) of the metal and the contact force.

Film Resistance

The presence of a film between the contacting surfaces generally results in high contact resistance since the films are either semiconductors or insulators. Extremely thin films may not be objectionable in some cases, but, normally, filming is to be avoided. The films are a result of surface reaction with the ambient atmosphere and usually consist of either oxides or sulfides. The filming tendency of metals varies, being least for members of the platinum - precious metals-group. Copper forms oxides and sulfides whereas silver exhibits only sulfide films. Platinum, rhodium and gold are essentially free of film formation at all temperatures up to their melting point.

E. Electrical Wear

Electrical wear in contacts is somewhat difficult to define accurately, but it indicates the general deterioration of the contact quality due to the arcing action that ensues when contacts are closed or opened. Opening of the contacts is generally the more severe case. The severity of the arcing that occurs on the opening of contacts depends upon the magnitude of the current and the voltage available to cause arcing. All materials possess a characteristic minimum arcing voltage in the 10 to 20 volt range. Above this voltage, arcing and loss of contact material due to arc erosion must be expected. As with other properties, contact metals possess varying degrees of resistance to arc erosion. Factors which enhance arc erosion resistance are: high melting point, high boiling point, high electrical and thermal conductivities and high minimum arcing voltage. Accessory

devices such as arc-suppressing capacitors or rectifiers are, of course, used in many applications, but these are outside the scope of the present study.

F. Fabricability and Cost

These are two factors which strongly influence the choice of materials for electrical contacts in almost all applications. In general, a material should be reasonably soft and ductile in order to be worked by conventional machinery and tooling processes. Also, the material, in addition to possessing desirable contact properties, should be available in sufficient quantities and at a cost that would not preclude its use. It is realized, of course, that in some electrical contact applications cost is not the major consideration, and in this case the chief problem becomes one of availability.

There is one class of contacts in which machinability considerations do not enter the picture, and this is the case of contacts prepared by powder metallurgy techniques. A powder mixture of the desired composition is pressed to shape and sintered (heated to a high temperature in a protective atmosphere) to densify and consolidate the pellet or button.

III. OPERATING CONDITIONS

A number of operating conditions must be considered before a material is selected for use in any given case. These conditions fall into three main classes as described below:

A. Electrical Conditions

Current - The nature of the current - whether a.c. or d.c. - and the actual value of the current in amperes, both at make and break, are major factors in the choice of contact materials. It is

also important to note that in many circuits the initial, transient current is much higher than the normal steady-state current.

One possible classification of contacts based on current levels may be given as follows:

1. Light duty applications, below 1.5 to 2 amperes
2. Medium duty applications, 2 to 5 amperes
3. Heavy duty applications, 5 to 20 amperes
4. Extra heavy duty applications, above 20 amperes

Voltage - Two types of voltage are involved in this consideration, open circuit voltage - or the voltage that would appear across a pair of contacts that "went open" -, and induced voltages that appear across a pair of contacts that are employed to open a reactive circuit rapidly.

B. Mechanical Considerations

Frequency of Operations - The number of times that a pair of electrical contacts are required to make and break an electrical circuit in a unit of time has a bearing on their service life. For contacts operated at high speeds (greater than 10 cycles/sec) the problems to contend with are arc erosion and local overheating. These problems, of course, persist to some extent as the frequency of operation is decreased. At very low frequencies--less than 1 per minute--these considerations are minor.

Contact Gap - This consideration applies to relays primarily and requires that the open circuit gap spacing be sufficient to prevent sustained arcing.

Contact Force - The contact force determines how intimately the two contact members are pressed together, and thus has an influence on the constriction resistance. Since contact materials vary widely in hardness, contact force plays an important role in the selection of materials. In general, the contact force on the make should be the maximum that the material will withstand without excessive deformation and mechanical wear.

Open Contacts - Contacts must operate reliably after remaining open for lengthy time periods. The contact materials must be capable of withstanding oxidation, corrosion and other chemical attack during extended idleness.

Method of Operation - Electrical contacts can be operated in a number of different ways, mechanical (by a cam), electrical (by a coil and armature), thermostatic (by a bimetal) and manual (by inserting a plug in a socket). The method used for any particular case will often affect the choice of materials.

C. Ambient Conditions

The ambient conditions under which the electrical contacts are expected to perform affect the choice of materials. Several variations encountered in ambient conditions may be cited, viz,

Gases or Vapors - The presence of gases or vapors can be detrimental to the operation of electrical contacts. Sulfur or sulfide-type atmospheres attack silver and can cause the development of insulative films. Organic vapors, e.g., gasoline, can be detrimental to contacts of the platinum group due to the formation of finely divided, insulating organic compounds on the contacts. Some platinum alloys serve as catalytic agents in this respect.

Foreign Materials - Dirt, dust, or other particulate matter may appear on the mating faces of electrical contacts and adversely affect their operation. The effect of dirty contacts is normally to increase arcing and pitting in power circuits and to prevent conduction in low-level circuits.

Temperature and Humidity - Contact materials employed in applications subject to elevated temperatures or in humid environments (particularly sea water air) must be capable of withstanding oxidation and corrosion.

IV. EVALUATION PROCEDURES

The only true evaluation of an electrical contact is its performance in the end equipment under the actual environmental conditions. This type of evaluation requires an extensive tabulation of performance data over a period of years to conclusively establish the reliability level of a given contact system. In some cases, even a functional life test gives only probabilistic results because the causes of failure are completely random in occurrence.

In a recent study of low-level relay contacts,[20] it was found that the major cause of contact failures (contact resistance above a fixed level) was the presence of particulate matter between the contact surfaces. This particulate matter was usually introduced during manufacture, and consisted of crystalized solder flux, cleaning abrasives, dust, and synthetic fibers. It was found that the results of short term load tests had almost no correlation with the eventual life of the relay, an indication that the effects of the particulate matter were random. In such a case, it is only possible to predict the reliability of a group or set of contacts because the reliability prediction of an individual contact is not meaningful. If a

similar condition exists in the connectors of interest to NASA, then the solution to the problem is in the direction of development of better manufacturing processes and storage procedures to minimize the presence of particulate contaminants, and the use of connectors which have high contact force and substantial contact wipe for more effective dislodging of the contaminants.

If, on the other hand, the causes of failure are systematic in origin, then the results of short term life tests may be valuable in predicting the eventual life of a contact pair. One such example is the presence of a tarnish or corrosion film on the contact surfaces. Under certain environments, this film may grow to such dimensions that the contact force and wipe are not sufficient to cause consistent disruption. In this case, variations in contact resistance would occur and could be detected in a short term life test. Such variations would be valuable in determining the expected reliability provided that the simulated conditions are realistic representations of the actual operating conditions. If the predominant cause of failures in the connectors of interest to NASA can be shown to be of film origin, then the logical approach for improvement would be to specify materials that are essentially film-free and mechanical designs that provide high contact force and increased wipe.

The most common method for evaluating a low-level contact pair is a contact resistance test. The resistance of the contact pair is usually determined from simultaneous readings of voltage and current or by direct indication of a shunt type ohmmeter. In performing contact resistance measurements on low-level contacts, the open-circuit voltage and load current magnitudes must be maintained below values that can cause electrical or thermal breakdown of the surface films. Review of

the technical literature has indicated that the metal to metal resistance of a given contact pair is relatively independent of the test voltage and current provided that they are well below the values necessary for non-mechanical film disruption. Acceptable values generally fall in the ranges of 10 to 50 millivolts open-circuit voltage and 1 to 40 microamperes load current.

Although the contact resistance test is of primary importance, other electrical parameters are sometimes measured to determine the merits of a particular contact system. Contact noise is one such parameter. Contact noise originates from the random motion of discrete charge carriers (thermal noise) and from spontaneous changes in the contact spots (current noise). Current noise is generally much larger than thermal noise, particularly when one member of the contact system is semiconducting. The measurement of contact noise usually includes the determination of amplitude and frequency distribution. For the connectors being considered in this program, it is not believed that contact noise is a predominant factor in the identification or mechanism of failures.

Thermoelectric effects are occasionally used to measure the effectiveness of a contact system, particularly when a temperature differential can exist across a contact system comprised of dissimilar metals. In such cases, a thermal emf can be generated which opposes the driving voltage and prevents conduction. In the common gold plated systems, the thermoelectric effects are usually negligible.

In addition to electrical measurements, various physical and chemical tests can be performed to give a qualitative indication of the value of a contact system. For example, in low-level systems, the presence of a surface film can be easily determined by measurement of

the coefficient of friction between sliding surfaces.[16] If an adsorbed film is present, the coefficient of friction will be substantially different from that which would be obtained if a metal to metal interface existed. The nature of the surface film can be determined by chemical or spectrographic analysis. Plastic replica techniques are often used for removing and studying contact deposits by electron microscopy.[17, 34]

The thickness of adsorbed film on a metal surface can be conveniently determined by measuring the contact angles of a known liquid on the coated surface.[16] Techniques have been evolved which permit the controlled contamination of a metal surface with a monolayer or finite number of layers of a known film.

The evaluation of plated contacts generally involves the qualitative determination of the thickness and uniformity of the plate. The thickness of plate is usually determined by photomicrograph of the cross-sections or by a chemical stripping process. The measurement of porosity is somewhat more difficult although a general indication can easily be obtained by immersing the plated object in an acid which attacks only the base metal. The measurement of weight loss provides a general measure of the degree of porosity. Diffusion of base metal through the plate can also be a contributing factor in the formation of a corrosion film, and a general indication of its degree can also be obtained by immersion in an acid bath.

V. SELECTION OF CONTACT MATERIALS

The general subject of electrical contacts has received intensive study both in the USA and abroad over the past one hundred years and a large body of literature relating to all phases of contacts and contact phenomena has grown up. This literature is widely separated in time and space and frequently is in a foreign language. The American Society for

Testing Materials recognized the necessity for a centralized listing of electrical contact literature and in 1951 undertook the assembly of literature and information on contacts in abstract form. The first publication covered literature from approximately 1840 to 1951. Each year thereafter a supplemental listing of newer literature has been issued. The latest issue covers information to the end of 1960. The present literature search on this project is based mainly on references and abstracts listed in the various ASTM supplements.

Before listing specific recommendations for contact materials, it will be of interest to examine in a general way the presently used materials and their properties. This will be done briefly in the sections below.

A. Copper and Copper Alloys

Copper is the second best electrical conductor (silver is better) of all the metals and is relatively cheap and workable. Copper also possesses high thermal conductivity. Pure copper is relatively soft and weak and can be strengthened by alloying with other metals e.g., copper plus zinc makes brass. The presence of the zinc however lowers the conductivity since the addition of any alloying agent invariably lowers the conductivity of the original material. Copper has a relatively low melting point (see Table I) and is subject to arc erosion damage. Furthermore, copper oxidizes easily at fairly low temperatures and also is attacked by sulfur vapors. For these reasons plain copper and its alloys find only limited applications in electrical contacts, where the above mentioned drawbacks are not objectionable. An example is the plug on a household electrical appliance. Here, there is appreciable contact force coupled with a degree of wiping action and low arc erosion. Spring brass serves well in this application and is very cheap.

Copper-base alloys can be employed in more demanding electrical contact applications if the mating surfaces are protected by a coating of a more noble, corrosion resistant material. Cladding and electroplating are two methods for applying the protective coating, and the most frequently employed materials are gold (or a gold alloy) and silver (or a silver alloy). Solder coatings are sometimes used, and they are applied by a dipping technique.

In the present study, one type of connector under consideration is the pin/socket configuration in which a number of circuits of low electrical levels are made or broken by manual operation of the plug. This application is admirably suited to the use of a copper alloy base material protected by a noble metal coating.

B. Precious Metals and Alloys

1. Silver and Silver Alloys

In many ways silver approaches the ideal contact material; it has the highest electrical and thermal conductivity of any metal, it is relatively cheap and plentiful, it is easily worked and it has good oxidation resistance at normal temperatures. On the debit side may be listed its softness (in pure form), its reactivity with sulfur and/or sulfide vapors at room temperatures and its low melting point. The drawb ack of low hardness can be minimized to certain extent by the choice of a proper alloying agent (most frequently copper) but the phenomenon of sulfide tarnishing cannot be easily avoided, and this precludes the use of silver or its alloys in critical, low-level circuits where high reliability is demanded. It is possible, of course, to alloy silver heavily with a more noble metal (such as palladium) and eliminate the tarnishing problem. However, the amount

required -- at least 50% by weight -- raises the cost excessively and increases the contact resistance.

In low power, a. c. circuits where the current is not too high (2 to 5 amperes), fine silver and its alloys can be used if the voltage is high enough at break to cause moderate arcing. Under these conditions, the sulfide tarnish films are ruptured and destroyed and the contact restored.

Silver and its alloys exhibit the phenomenon of metal transfer in certain applications where arcing at break occurs. Metal transfer, as its name implies, consists in the movement of metal from one contact to the other. The normal explanation for this action involves the vaporization of local areas on the face of the contact with migration of the evaporated atoms along the arc. Silver has a low melting and boiling point and would thus be susceptible to this type of contact deterioration.

Despite the drawbacks cited above, silver and its alloys are the most important contact in the light and medium duty areas.

2. Gold and Gold Alloys

Pure gold possesses a number of desirable features as an electrical contact material. It is completely free of oxidation or corrosion under nearly all conditions. It has favorable electrical and thermal conductivities and exhibits a low and constant value of contact resistance. Among its drawbacks may be cited, high cost ($35 per troy ounce), low hardness and low melting point. The inherent softness of pure gold coupled with the low melting point leads to welding and contact sticking. As in the case for silver, the low hardness of gold may be increased by alloy additions (such as copper or silver) but the amount added must be limited to a level at which the inherent corrosion-resistant properties of

the parent metal are not degraded. It should also be mentioned that the addition of alloying ingredients markedly lowers the electrical conductivity.

A practical method for obtaining the desirable contact properties of gold at a reasonable cost is by electroplating. Here a thin coating of gold or a gold alloy is applied by electrolytic means to the basis metal of the contact. A detailed Military Specification (MIL-G-45204) has been issued to cover the production of gold plated articles for government use. Gold plated contacts are suitable for applications in which contact forces are low, sliding is minimal, make and break frequency is low and electrical signals are small. These conditions are encountered in a variety of manually operated plug/socket type of connectors used in dry circuits. Pure plated gold is soft and subject to mechanical wear, and frequently an alloy electrodeposit is used (often with up to 2% Ni) in order to obtain improved wear resistance.

3. Platinum Metals

The platinum family of metals consists of platinum, palladium, rhodium, iridium, osmium, and ruthenium. Complete freedom from all forms of tarnishing, high melting points and great hardness make these metals and their alloys attractive as contact materials for light duty applications. Of the six metals, only two platinum and palladium, have found significant use in electrical contacts, see Table II. Other members of the group are brittle and virtually unworkable, and they find use only as alloying agents in precious metal contacts. Rhodium has the best electrical conductivity of the group (36% IACS) and can be applied as an extremely hard, corrosion resistant electrodeposit on contact surfaces. Palladium and platinum have about the same electrical conductivity (16% IACS);

platinum however is much more oxidation resistant at high temperatures. All members of the platinum family are expensive ranging from approximately $25 per Troy ounce for palladium to $125 per Troy ounce for rhodium. In this connection it might be pointed out that palladium is cheapest noble metal except silver.

C. Recommended Materials for Electrical Contacts

1. Dry Circuits

Dry circuits are characterized by low levels of current and voltage and low contact forces. The lower limits of current and voltage specified for study in this work -- 1 microampere and 200 millivolts -- are definitely in the dry circuit category. The prime requirement of electrical contacts operating in this region is complete absence of tarnishing or film forming tendencies under the conditions of use. Other considerations such as contact resistance and cost -- while admittedly important -- must be secondary to this requirement. From this viewpoint, the best materials in order of preference would be rhodium, platinum, gold and palladium. As mentioned previously, rhodium is not normally employed as a bulk contact material but as a corrosion resistant coating. Although pure platinum, gold or palladium are used in some ultra-reliable contact applications, the softness of these metals precludes their use in many cases, and recourse to alloys is indicated. Table II lists a number of alloys of this type in decreasing order of oxidation and corrosion resistance.

The cost of precious metals is high, and advantage should be taken of all methods that will reduce the amount of the precious metal required in a contact without sacrificing the desirable properties of the costly material. A widely used process for achieving this end is electro-

deposition of the desired precious metal (usually gold, sometimes rhodium) on a suitable basis metal. Gold plated phosphor bronze or copper is recommended by some investigators but this must be approached with caution. All electrodeposited metals exhibit porosity below some limiting thickness, and consequently bare basis metal may exist in micro-spots on an apparently "covered" contact.[11, 13] Corrosion of the basis metal can take place through these pores, corrosion products can build up on the interface between two closed contacts and the circuit develop an "open". Another type of failure in gold plated contacts can occur if there is appreciable diffusion of atoms of the base through the gold to the surface. As in the case of porosity, the basis metal atoms oxidize or tarnish and open the circuit. One other source of possible insulative surface films on the gold plating is from the alloying atoms in the plate itself. If these atoms react with the atmosphere, conceivably an open circuit condition could be caused.

Another possible cause for poor performance in gold plated contacts is the variability in the quality of gold plating from different platers.[11] Wide variations in the ability of nominally identical gold electroplates to protect an underlying silver surface were seen in specimens plated at various places in the country. Plating is still an art and not a science, and even identical baths and procedures sometimes give divergent results. The basic mechanism of electrodeposition is not clearly understood, including a variety of factors that can cause "pinholing," roughness, non-adhesion or off-composition deposits.

2. Light Power Circuits

The upper range of current and voltage listed for study in this work is 5 amperes and 500 volts. This range falls in the light power area and the selection of a material for this duty depends upon the type of service involved, the contact forces involved and the degree of inductive arcing that can develop as a result of circuit reactance and speed of contact opening. Low power control circuits were specified as of interest, and a widely used method of contact operation in this type of circuit is the electromagnetically operated relay. Pure silver is a good contact material at currents greater than about 0.4 ampere and voltages in the region of 110 volts a.c. For more severe applications -- as when appreciable arcing happens at break -- a number of silver-base alloys are available, see Table II. Palladium is sometimes used for light power electrical contacts, but its electrical conductivity is greatly inferior to that of silver. An improved contact material based on silver was developed by dispersing cadmium oxide (CdO) in a silver matrix. The effect of the CdO was to reduce welding and sticking tendencies, enhance arc erosion resistance and increase resistance to transfer and pitting in the silver. This material is recommended for light duty relay service at currents up to 30 amps and voltages up to 300 volts. In decreasing order of merit, after the Ag-CdO composition, are fine silver, silver-copper alloys, silver-copper-nickel and palladium. The latter material, although showing low electrical conductivity, 16% IACS, has low contact resistance properties and would be suited to low contact force relays.

VI. SUMMARY AND CONCLUSIONS

The literature survey has disclosed the vast amount of work that has been carried out on electrical contact materials and the multitude of complex phenomena that attend the making and breaking of electrical circuits. Also discussed were the numerous physical properties required in contact materials to serve in various applications. An ideal contact material does not exist since conflicting requirements must be met in the various types of service. In the present instance the circuits of interest to NASA comprise low-level, signal circuits (dry circuits) and light duty control circuits. In the former case, the chief concern relates to reliability of contact under low currents, voltages and contact forces and dictates a material that is free from oxidation or film forming tendencies. This requirement is met by the precious metals platinum, gold and palladium and alloys thereof. Cost considerations limit the use of platinum and its alloys to cases where only small amounts of actual contact material are required, such as small button type contacts or the like. In cases where the size and/or number of the contacts are large -- such as a multi-contact plug/socket assembly -- the cost of solid gold or palladium contacts would likewise be too high. A practical solution to this type problem is to employ a base metal overlaid with a thin coating of the precious metal. Although palladium plating is possible, gold plating is a much more common process.

The use of a plated gold coating on a base metal to provide a bulk contact with an oxidation and tarnish resistant outer surface is basically a sound approach to the problem of low level contact materials. However, such contacts must be carefully made to avoid the appearance of insulative

films on the surface of the gold. These films are the result of foreign atoms that oxidize or tarnish on the gold surface. Diffusion of base metal ions through the gold or the presence of other atoms in the gold itself (from the plating process) are two sources of foreign atoms. Porosity in the gold coating permitting oxidation of the base material is another source of trouble. One fruitful area of experimental work is in the investigation of methods for avoiding the development of these insulative films along the following lines:

1. Investigate the feasibility of the use of a barrier layer on the base metal that will prevent diffusion of the offending atom (s).

2. Investigate the use of a precious metal alloying addition in the gold plating bath instead of the presently used copper or nickel. (Alloy gold plate is employed to avoid the softness of pure gold)

3. Investigate the feasibility of a completely different approach to the problem of dry circuit electric contacts, e.g., examime the merits of an oxidation resistant base metal such as one of the stainless steels. (It is realized that soldering and/or crimping considerations must be made also for the lead connections in plug/socket connectors).

In the case of light duty contacts operating at currents between 0.5 and 5 amperes and with circuit voltages up to 500 volts a.c. or d.c., the chief requirements for the contacts in a control device such as an electromagnetic relay are: good electrical and thermal conductivity, good arc erosion resistance, low metal transfer and freedom from welding or sticking. This problem area is best served by a composite compact material consisting of cadmium oxide dispersed in a silver matrix. The normal manufacturing technique for this material involves powder metallurgy; however, a new method for producing Ag-CdO mixtures has been

reported in which Ag-Cd alloys are given a suitable oxidation treatment. For light duty contact uses in which the superior properties of the Ag-CdO alloy are not indicated, pure silver or silver alloyed with copper can be employed.

Table I. Some Properties of Copper and Copper Alloys Used for Electrical Contacts[a]

Alloy	Melting Point F	Electrical Conductivity % IACS (b)	Rockwell Hardness		Tensile Strength	
			Annealed	Hardened	Annealed	Hardened
0.04 oxide	1949	100	F40	B40	32,000	42,000
1.25 Sn + P	1900	48	F60	B64	40,000	55,000
5 Sn + P	1750	18	B26	B78	47,000	68,000
8 Sn + P	1620	13	B32	B84	55,000	76,000
15 Zn	1810	37	F56	B65	40,000	57,000
20 Zn	1770	32	F57	B70	42,000	61,000
35 Zn	1660	27	F68	B70	49,000	61,000
2 Be + Ni or Co (c)	1587	17-21	B60	B93	72,000	95,000

(a) Table from Metals Handbook, 8th edition, 1961

(b) International Annealed Copper Specimen

(c) A heat treatable alloy

Table II. Some Properties and Costs of Precious Metals and Alloys Used for Electrical Contacts (a)

Alloy	Melting point (solidus), F	Oxidation resistance	Corrosion resistance	Electrical conductivity, % IACS	Rockwell 15T hardness Annealed	Rockwell 15T hardness Hardened	Density, troy oz per cu in.	Metal cost, $ per cu in.
Silver and Silver Alloys								
Fine Silver	1760	High	Low	106	30	75	5.53	$ 5.09
92.5 Ag – 7.5 Cu	1510	Low	Low	85	65	83	5.46	4.64
90 Ag – 10 Cu	1430	Low	Low	85	70	84	5.43	4.50
72 Ag – 28 Cu	1430	Low	Low	87	77	84	5.30	3.51
72 Ag – 26 Cu – 2 Ni	1430	Low	Low	60	75	88	5.30	3.51
85 Ag – 15 Cd	1610	Low	Med	35	45	83	5.36	4.20
97 Ag – 3 Pt	1800	High	Med	50	48	78	5.62	17.50
97 Ag – 3 Pd	1790	High	Med	60	48	80	5.55	8.50
90 Ag – 10 Pd	1830	High	Med	30	62	82	5.61	17.00
90 Ag – 10 Au	1780	High	Med	40	56	75	5.77	25.00
60 Ag – 40 Pd	2240	High	Med	8.0	77	87	5.82	45.00
70 Ag – 30 Pd	2120	High	Med	12	72	85	5.75	34.00
Platinum and Platinum Alloys								
Platinum	3220	High	High	16	60	78	11.30	757.00
95 Pt – 5 Ir	3230	High	High	9	71	86	11.33	762.00
90 Pt – 10 Ir	3240	High	High	7	78	90	11.34	769.00
85 Pt – 15 Ir	3250	High	High	6	86	92	11.36	775.00
80 Pt – 20 Ir	3290	High	High	5.6	86	93	11.40	783.00
75 Pt – 25 Ir	3310	High	High	5.5	90	95	11.42	788.00
70 Pt – 30 Ir	3360	High	High	5	93	97	11.46	794.00
65 Pt – 35 Ir	3450	High	High	5	96	98	11.48	801.00
95 Pt – 5 Ru	3240	High	High	5.5	84	92	10.90	721.00
90 Pt – 10 Ru	3270	High	High	4	88	95	10.52	686.00
89 Pt – 11 Ru	3300	High	High	4	90	96	10.45	681.00
86 Pt – 14 Ru	3350	High	High	3.5	94	97	10.22	662.00
96 Pt – 4 W	3230	High	High	5	85	93	11.34	730.00
Palladium and Palladium Alloys								
Palladium	2830	High	High	16	65	80	6.32	114.00
95.5 Pd – 4.5 Ru	2900	High	High	7	73	86	6.33	122.00
90 Pd – 10 Ru	3000	High	High	6.5	87	93	6.34	134.00
70 Pd – 30 Ag	2510	High	High	4.3	80	90	6.07	78.00
60 Pd – 40 Ag	2440	High	High	4.0	72	90	5.98	67.00
50 Pd – 50 Ag	2350	High	High	5.5	78	89	5.90	56.00
72 Pd – 26 Ag – 2 Ni	2520	High	High	4	80	90	6.08	81.00
60 Pd – 40 Cu	2190	Low	Med	5	83	95	5.57	63.00
45 Pd – 30 Ag – 20 Au. – 5 Pt	2500	High	High	4.5	88	96	6.59	124.00
35 Pd – 30 Ag – 14 Cu. – 10 Pt – 10 Au – 1 Zn	1985	Low	High	5	90	97	6.25	105.00
Gold and Gold Alloys								
Gold	1985	High	High	75	25	65	10.18	357.00
90 Au – 10 Cu	1710	Med	High	16	76	91	9.13	287.00
75 Au – 25 Ag	1885	High	High	16	43	80	8.42	224.00
72.5 Au – 14 Cu – 8.5. Pt – 4 Ag – 1 Zn	1750	Med	High	10	88	96	8.49	264.00
69 Au – 25 Ag – 6 Pt	1885	High	High	11	75	90	8.46	245.00
41.7 Au – 32.5 Cu – ... 18.8 Ni – 7 Zn	1940	Low	Med	4.5	88	96	5.93	86.00

(a) Table from Metals Handbook, 8th edition, 1961

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ATMOSPHERIC CONDITIONS AT CAPE CANAVERAL

I. Introduction

This appendix contains the results of a brief study of available data on atmospheric conditions at Cape Canaveral. These results are presented in two parts. The first, in Section II, gives mean and extreme values of pertinent meteorological variables, derived from records of the Cape Canaveral weather station. The second part, in Section III, is a discussion of the chemistry and the mechanics of production and deposition of sea salt.

II. Mean and Extreme Weather Conditions at Cape Canaveral

The mean and extreme values of meteorological variables at Cape Canaveral are listed in the following tables. The periods of record from which these statistics are calculated are as follows.

	Table Number and Description	Period of Record
1,	Frequency of Daily Maximum Temperature	July 50 - Jan. 53 July 53, Nov. 56 - July 60
2,	Frequency of Daily Minimum Temperature	Same as Table 1
3,	Frequency of Daily Mean Temperature	Same as Table 1
4,	Frequency of Daily Rainfall Amount	Sept. 50, Nov. 50, Sept. 51, Nov. 51 - Nov. 52, Dec. 56 - July 60
5,	Annual Percent Frequency of Wind Direction by Speed Groups	June 50 - Feb. 54 April 54 - July 60
6,	Maximum Winds Observed	June 50 - Feb 54, April 54, April 56 - July 60
7,	Peak Gusts Observed	Oct. 57 - March 58, Feb. - July 59
8,	Percent Frequency of Selected Weather Phenomena	Same as Table 6
9,	Mean and Standard Deviation of Relative Humidity by Months	Same as Table 6

Table 1

Frequency of Daily Maximum Temperature

Temperature, deg F	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
42-3												1	1
44-5	1												1
46-7	1	1											2
48-9	4												4
50-1	2	4									1	1	8
52-3	4	4	2									2	12
54-5	5	2	2								2	1	12
56-7	4	5									3	3	15
58-9	8	4	4								4	4	24
60-1	6	6	2								3	9	26
62-3	13	11	10	1							2	10	47
64-5	15	7	12	3						2		15	54
66-7	18	12	12	4							6	13	65
68-9	16	21	18	9						1	10	13	88
70-1	19	16	21	10	4					2	11	22	105
72-3	27	14	24	10	2					6	14	24	121
74-5	25	21	20	27	1					10	28	26	158
76-7	18	13	28	27	12	1				11	28	28	166
78-9	16	16	11	36	27	2	2		3	17	34	14	178
80-1	7	6	9	30	34	8	2	3	6	33	21	4	163
82-3	1	5	7	13	45	25	7	6	13	43	18		183
84-5		2	3	4	38	46	18	25	39	28	6		209
86-7			1	3	17	50	80	47	79	16	1		294
88-9				2	6	27	75	63	32	9			214
90-1						10	27	22	5	1			65
92-3						7	3	15	2				27
94-5						1		2	1				4
96-7						2							2
98-9						1							1
Monthly Mean	68.7	69.6	71.8	76.7	81.8	86.0	87.3	87.7	86.1	81.3	75.0	70.2	78.5

Table 2

Frequency of Daily Minimum Temperature

Temperature, deg F	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
26-7												1	1
30-1	1	2									1		4
32	2	1											3
33	2	2											4
34-5	4	2									1	2	9
36-7	8	5									3	3	19
38-9	7	5	2								4	7	25
40-1	5	8	3								3	6	25
42-3	10	4	5								4	6	29
44-5	9	4	9								4	11	37
46-7	12	6	11	2							8	17	56
48-9	18	13	11	5							1	10	58
50-1	13	13	13	2						2	10	11	64
52-3	17	7	7	5						2	5	10	53
54-5	19	10	13	10	7					3	2	7	71
56-7	11	19	18	9	1					4	5	10	77
58-9	18	18	13	18	6					6	8	17	104
60-1	17	14	12	21	8	1				3	17	20	113
62-3	19	12	23	15	10					4	20	19	122
64-5	7	19	26	21	14	2				7	20	15	131
66-7	10	5	13	19	19	7		1		11	23	13	121
68-9	1	1	5	25	41	12	4	4	4	18	25	4	144
70-1			2	25	35	36	22	16	16	32	21	1	206
72-3				2	29	53	62	48	47	49	7		297
74-5					15	48	77	69	58	31			298
76-7					1	19	29	35	40	7			131
78-9						1	13	10	13				37
80-1						1	4		2				7
82-3							1						1
84-5							2						2
Monthly Mean	52.3	53.5	56.7	62.8	68.0	72.5	74.1	74.1	74.3	69.5	60.7	54.4	64.4

Table 3

Frequency of Daily Mean Temperature

Temperature, deg F -	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
34-5												1	1
38-9	2												2
40-1	2	1											3
42-3	3	4										1	8
44-5	5	3	1								2		11
46-7	5	2	2								2	5	16
48-9	6	7	1								5	1	20
50-1	5	6	2								5	7	25
52-3	10	7	7								2	9	35
54-5	15	6	12								3	19	55
56-7	9	6	4	3							3	7	32
58-9	23	14	14	3						2	7	12	75
60-1	18	15	16	6						1	5	11	72
62-3	17	17	15	10	1						8	19	87
64-5	21	18	19	12	3					6	11	19	109
66-7	24	17	20	16	4					7	10	23	121
68-9	22	18	25	25	10					4	25	19	148
70-1	16	11	19	23	13					8	29	22	141
72-3	5	12	14	27	18	2				10	23	9	120
74-5	2	6	14	36	38	8	2	4	1	25	30	6	172
76-7				15	51	29	7	5	10	46	16		179
78-9			1	2	39	45	35	23	43	49	6		243
80-1			1	1	9	57	96	74	77	15			329
82-3						30	58	57	43	6			194
84-5						7	13	20	6				46
86-7						2	3						5
Monthly Mean	60.6	61.9	64.5	70.0	75.1	79.5	80.9	81.1	80.4	75.6	68.0	62.5	71.7

Table 4

Frequency of Daily Rainfall Amount

Amount, inches	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
None	114	99	113	118	108	99	110	85	75	70	115	96	1202
Trace	12	19	16	18	26	19	15	20	27	22	20	20	234
0.01	1	6	3	4	5	4	5	3	4	3	3	5	46
0.02-0.05	9	7	8	8	10	6	8	4	13	10	14	10	107
0.06-0.10	3	8	7	6	14	2	6	8	6	10	7	5	82
0.11-0.25	3	5	14	8	5	14	17	9	15	14	6	8	118
0.26-0.50	3	10	8	7	10	18	11	12	16	8	3	5	111
0.51-1.00	4	9	8	5	6	13	8	6	14	8	6	3	90
1.01-2.50	5	7	7	5	2	5	6	8	8	8	6	3	70
2.51-5.00	1		1	1					2	1			6
5.01-10.00			1							1			2
Total number of days	155	170	186	180	186	180	186	155	180	155	180	155	
Monthly Mean	2.85	3.69	5.10	3.08	2.31	4.21	4.21	4.48	6.70	6.97	2.59	1.96	48.12

Table 5

Annual Percent Frequency of Wind Direction by Speed Groups

Direction	Speed, knots 1-3	4.10	11-21	22-27	Mean speed, knots
N	0.6	3.1	2.5	0.1	9.7
NNE	.4	2.5	1.1		8.6
NE	.6	3.5	1.4		8.4
ENE	.5	3.2	1.5		8.8
E	.9	7.0	2.3		8.3
ESE	.6	5.6	1.7		8.1
SE	.9	6.2	2.1		8.2
SSE	.6	4.1	1.5		8.5
S	.9	5.2	1.4		7.7
SSW	.5	2.8	0.7		7.4
SW	.9	2.9	.6		6.8
WSW	0.6	1.8	0.4		6.8
W	1.0	3.7	1.2	0.1	7.7
WNW	0.6	2.7	1.1		8.1
NW	.8	3.9	1.8	0.1	8.4
NNW	0.5	2.1	1.4	0.1	9.1

Table 6

Maximum Winds

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Direction	NW	WNW	ESE	NW	ENE	SSE	SSW	SE	SE	E	NW	W
Speed, knots	28	30	34	28	23	26	31	22	35	36	30	25

Table 7

Peak Gusts

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Direction	N	W	NNW	WNW	NW	WNW	W	*	*	N	NNW	WNW
Speed, knots	37	41	44	38	37	43	34			30	26	30

*No winds observed which met the criteria for gusts.

Table 8

Percent Frequency of Selected Weather Phenomena

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Thunderstorm	0.1	0.2	1.2	1.0	2.6	3.8	5.0	5.3	2.9	1.2	0.5	0.1
Rain and/or Drizzle	4.8	7.0	7.7	4.6	3.2	5.1	3.6	4.3	6.9	8.4	3.3	5.2
Fog	6.7	4.4	2.7	1.0	0.7	0.4	0.1	0.5	0.4	1.0	2.2	4.4
Smoke and/or Haze	0.5	0.3	0.3	0.2	0.1	0.2		0.2	0.4	0.2	1.2	0.5
Dust and/or Sand			0.2									

Table 9

Mean and Standard Deviation of Relative Humidity by Months

Month	Mean Relative Humidity, %	Standard Deviation of Relative Humidity, %
Jan.	80.3	15.5
Feb.	80.5	15.7
Mar.	78.1	16.3
April	76.4	14.6
May	77.2	14.1
June	79.7	12.3
July	82.1	10.9
Aug.	83.2	11.3
Sept.	81.6	11.2
Oct.	80.1	13.1
Nov.	78.5	14.2
Dec.	79.9	15.0

III. Sea Salt

Corrosion due to sea salt can contribute to electrical contact failure. This section contains a discussion of several pertinent aspects of the sea salt problem.

a. Production of Particles

Because sea salt particles can serve as condensation nuclei for formation of fog and cloud droplets, their production and distribution in the atmosphere has been studied by a number of investigators.[1-3] Boyce[4] found that most of the nuclei produced by a breaking wave did not come from the actual breaking of the wave, but from the bubble and foam patch subsequently formed by the wave. Blanchard[5] thoroughly examined the production of salt particles by collapse of bubbles. He found that the majority of the sea salt particles that arise from the sea come from collapse of the bubble film and the breakdown of a jet which rises at high speed from the bottom of the collapsing bubble cavity.

The detailed mechanics of bubble collapse and jet breakdown are not of interest here; it is sufficient to point out that much of the bubbling activity of the ocean takes place along the shore, and thus the local sea salt concentration at Cape Canaveral can be expected to be higher than that at inland locations. Investigators have also found that ocean spray which is large enough to be easily seen (as a mist) is not a significant source of sea salt. This is because the droplets are too large to travel far before they fall to the surface.

b. Chemistry of Sea Salt

It is generally accepted that large nuclei have the same composition as sea water, but there is little agreement on the chemical composition of nuclei less than 2 μ in diameter.[6] It must be remembered that the nuclei which originate in the sea come not from the bulk water, but from the surface layer, whose composition, especially with respect to organic content, may not be that of bulk sea water. Woodcock[7] showed that nuclei resulting from bubbling effectively removed oleic acid films from the surface of sea water.

The salts in sea water are hygroscopic, that is they have an affinity for water vapor, so that water condenses on them at relative humidities well below 100%. Thus, dry sea salt particles which impact on a surface

and are exposed to ambient relative humidity above about 78% become concentrated brine droplets. This enhances their ability to migrate over the surface, as well as their corrosive activity. Since NaCl has a lower critical relative humidity than other constituents of sea salt, and is much more abundant, the controversy about exact chemical composition of salt particles is of no concern here. Figure 1 illustrates the influence of ambient relative humidity on sodium chloride droplets.

C. Concentration and Size Distribution of Sea Salt

Since interest in production of sea salt has centered on its importance as nuclei for cloud formation, the only extensive and accurate measurement of concentration and size distribution have been made with airborne samplers. However, Durbin and White[9] recently found little variation in the atmospheric sea salt load in the lower 5000 ft, so measurements within this layer will be taken as representative of surface measurements.

The major conclusions to be drawn are:

1. Wind speeds less than 20 mph, and wave heights less than 5 ft are not significantly correlated with particle concentration.
2. Sea salt particles of mass 10^{-13}* to 7×10^{-8} grams occur in concentrations up to at least 230 μgm^{-3}*. Median mass is up to 10^{-9} g.

These values should be representative for any location not in the spray zone, since the very large droplets raised by wave action have no opportunity to dry out and become airborne before they fall back into the sea.

Since measurements at Cape Canaveral were not available and no knowledge of topography or vegetation which might modify the local transport of sea salt, values based on the work of Durbin and White will be assumed. The sea salt aerosol will be assumed to contain 1 particle

* $1 \mu g = 10^{-6} g$

cm^{-3}, and a total salt load of $200 \mu gm^{-3}$. Thus, the mass of a particle is $2 \times 10^{-4} \mu g$, and its diameter is 5.5μ .**

Salt particles of this size settle in still air at a speed of 2 mm sec^{-1}. With the assumed concentration, deposition by sedimentation on a horizontal surface amounts to 1 particle every 5 sec per cm^2 of surface. This figure for deposition rate is nominal. Many other factors, including wind speed, degree of turbulent mixing, and the shape of the object, may influence the collection efficiency.

** $1 \mu = 10^{-6} m$

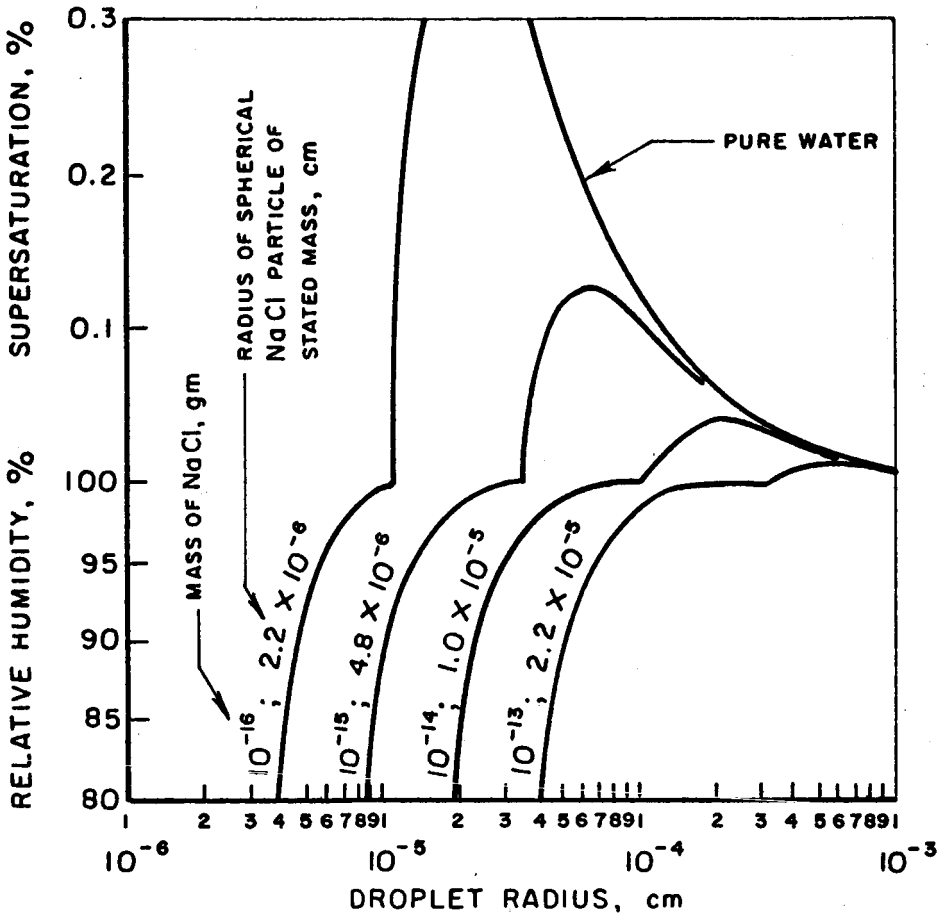

FIG. 1 EQUILIBRIUM RELATIVE HUMIDITY AND SUPERSATURATION FOR DROPLETS OF NaCl SOLUTION (AFTER MASON[8])

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